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NEW CONCEPTS IN ELECTROMAGNETIC MATERIALS AND ANTENNAS

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Antennas & Electromagnetics Technology Branch
Multispectral Sensing & Detection Division

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Interim Report

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14. ABSTRACT
The overall objective of this research is to develop antenna and sensor systems that will meet the Air Force's ever-increasing demand for reduced cost, size, weight, and power (CSWAP) while maintaining or increasing system functionality. This basic research effort consists of several sub-tasks that use analytical and numerical methods to examine the interaction of metamaterials and antennas, topics in transformation optics, and performance limitations of antennas on artificial magnetic grounds and unmanned aircraft systems (UAS). This interim report summarizes the first 20 months of a three year effort.

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1 EXECUTIVE SUMMARY

The overall objective of this three year research project is to develop antenna and sensor systems that will meet the Air Force's ever-increasing demand for reduced cost, size, weight, and power (CSWAP) while maintaining or increasing system functionality. This basic research effort consists of several sub-tasks that use analytical and numerical methods to examine the interaction of metamaterials and antennas, topics in transformation optics, and performance limitations of antennas on artificial magnetic grounds and unmanned aircraft systems (UAS). Specifically, this in-house research and development program consists of four sub-tasks which are: 1) Metamaterial Inspired Superstrates for Smart Antenna Systems (Dr. Jeffery Allen). 2) Bandwidth Limitations of Antennas on Artificial Magnetic Grounds (Dr. Herscovici). 3) Topics in Transformation Optics and Metamaterials (Dr. Bae-Ian Wu). 4) Fundamental Performance Limitations of Antennas Mounted on Electrically Small UAS (Dr. Kramer). The objective(s) for each sub-task is briefly stated below.

1. Subtask 1: Metamaterial Inspired Superstrates for Smart Antenna Systems
    - Create simplified methods that combine material and physical modeling approaches to understand how the behavior of phased array antenna systems can be modified using metamaterial superstrates.
2. Subtask 2: Bandwidth Limitations of Antennas on Artificial Magnetic Grounds
    - The objective is to determine and compare bandwidth limitations of antennas on artificial magnetic grounds (AMG) and traditional perfectly conducting (PEC) ground planes as a function of the separation between antenna and the AMG/PEC plane. The goal is to examine the trade-off between bandwidth and separation for the two types of ground planes that are common to low-profile antennas.
3. Subtask 3: Topics in Transformation Optics and Metamaterials
    - In the first year of research, the objectives from the proposed graphene study are to yield a better understanding of electromagnetics in graphene-based structures and provide new theoretical tools regarding the guidance properties of graphene-based transmission line for metamaterial devices and sensors in the mm-wave and optical frequencies.
    - For the transformation optics/metamaterial research, the objectives would be to establish a working code based on analytic technique for the study of the antenna problem. The configuration for such hybrid analytic studies will be of canonical shapes, including planar, cylindrical, and spherical with or without the presence of ground plane. Conformal antenna based on transformation optics would be the next step. At the same time, the feasibility of using spectral transformation and surface current based media inversion is expected to be completed by the first year mark.
4. Subtask 4: Fundamental Performance Limitations of Antennas Mounted on Electrically Small Unmanned Aircraft Systems (UAS)
    - The goal of this effort is to establish performance limits for antennas mounted on structures (e.g. UAS, Micro-UAS, etc.) with sub-wavelength dimensions.

The remainder of this report discusses the objectives in more detail and summarizes the results of the first 20 months of this three year project.

2 Subtask 1: Metamaterial Inspired Superstrates for Smart Antenna Systems

In compact phased arrays, only a small number of antenna elements are available. This directly determines and limits the number of degrees of freedom that are available for adaptive beam/null-forming. It limits the number of nulls/beams that the system can steer, where these null/beams can be placed and their quality as well as the gain of the system [1]. Therefore, for a given processing algorithm, system performance can be improved either by increasing the number of antennas available, increasing how efficiently the aperture is being used, or preferentially moving available performance (e.g. ability to suppress jammers) to critical areas of scan space thus improving performance in those regions. The use of quasi-optical elements to enhance the performance of phased array anti-jam and beam steering systems has been and continues to be of great practical interest. Recent developments in engineered materials suggest even greater design possibilities for overcoming system limitations than were previously available with standard dielectric materials. Metamaterial-based devices provide additional degrees of design freedom (e.g. inhomogeneity, anisotropy, tenability, etc.) in defining the precisely spatially distributed material parameters and the ability to adjust and optimize them so as to balance the various tradeoffs in the system.

2.1 Objectives

Our objective is to use numerical approximation methods to reduce the complexity of metamaterial superstrate designs. The research will focus on developing a simplified methodology to solve the inverse problem which uses the system behavior described by the far-field radiation characteristics to calculate the material parameters that result in the required performance. We will develop this method in the context of metamaterial superstrates that give the desired system performance in antennas, phased array antenna and scattering. This investigation also aims to show how metamaterial superstrates can be designed to improve far-field characteristics, scattering problems and overall system performance of antenna systems.

2.2 Technical Summary

2.2.1 First Year Summary

During 2012 this subtask consisted of setting up, configuring and coding the software problem in Matlab and computational electromagnetic solvers (Comsol [2] and HFSS [3]). In addition, we developed analytical and full-wave electromagnetic simulation models for the scattering problem to show the efficacy of using basis functions as a method to optimize material properties that result in a desired effect such as a predefined far-field pattern or reduction in scattering cross-section. Conducted detailed literature search to help devise novel models to accurately determine and modify material properties of given electromagnetic structure. We also setup up requisite hardware (high performance computational computer for multi-threading) in conjunction with configuration of computational software to maximize performance and speed of aforementioned simulations.

Our initial problem has concentrated on controlling the scattering of cylinders. Using basis functions to represent the spatial distribution of material properties, we started exploring the inverse problem of minimizing scattering or shaping the far-field scattering profile to a pre-defined profile.

This task began in fiscal year (FY) 2011, and is scheduled to be completed in FY13. Next year we plan to continue working on the scattering problem and also extend the model to the radiation problem. Specifically, we will modify the current setup to include calculation of metrics (e.g. total scattering cross section) that measure the performance of the simulations. We will then extend the simulations to three dimensions.

2.2.2 Second Year Summary

During 2013 this subtask consisted of two major objectives: demonstration of a passive optimized component (lens) and inclusion of active source into the passive transformed space for a cohesive combined transformation. We use the source transformations approach to manipulate antenna arrays such that the physical location/shape is dictated by the system (e.g. wing/fuselage) and the electromagnetic performance is defined by the application. Numerical simulations how an array with sources arranged in a circular manner can be surrounded by a transformation optics medium so that it can be made to receive and radiate as if it were a linear array of uniformly spaced elements and vice versa. We have finished setting up, configuring and coding the software problem in Matlab and computational electromagnetic solvers (Comsol) for full-wave electromagnetic simulation models where the shape of individual sources was changed using Source Transformation Optics (STO). This first set of simulations provided solutions to the ideal case and valuable information into the upper bounds defined by the physics of the problem. This information will be used in optimization routines to develop appropriate approximate Transformation Optics (TO) media with practical parameters that can be fabricated and measured using standard testing procedures.

2.3 Future Work

Next, we will: (i) Derive analytical solutions based on form-invariant Maxwell's equations in the STO framework for the transformed sources as well as TO media; (ii) Develop in-house Matlab code to simulate the passive TO case operation that can provide insight into the wave propagation in the designed media; (iii) Perform finite element method (FEM) based simulations using software packages such as Comsol® to predict the behavior of untransformed and transformed arrays; and (iv) Compare results from (iii) with respect to EM fields and far-field patterns to demonstrate the efficacy of the approach.

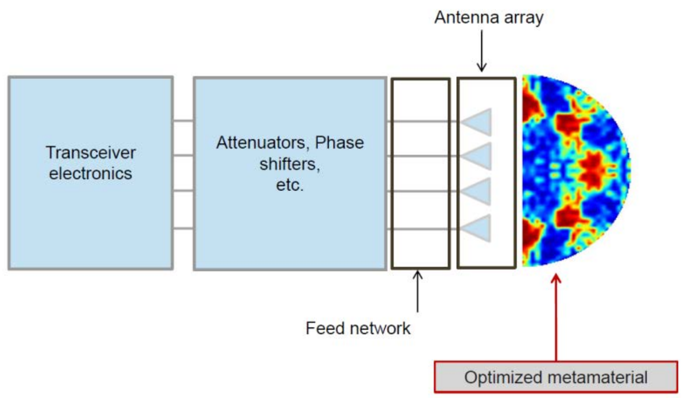

Figure 1 System Overview

3 Subtask 2: Bandwidth Limitations of Antennas on Artificial Magnetic Grounds

This research concerns the broadband matching limitation for an arbitrary radiator over an Artificial Magnetic Ground (AMG). A lot of work has been done in the design and optimization of Artificial Magnetic Grounds to make them behave as perfect magnetic conductor (PMC) grounds. It is well known that a dipole located at λ/4 over a perfect electric conductor (PEC) ground will radiate in phase with the reflective wave (**Figure 2**a). Alternatively, a dipole located on a Perfect Magnetic Ground will also radiate in phase with the reflective wave. Since PMC do not exist in nature, the concept of AMG was introduced. Since locating the dipole on the AMG will short the AMG, the dipole needs to be located in the proximity of the AMG (**Figure 2**b).

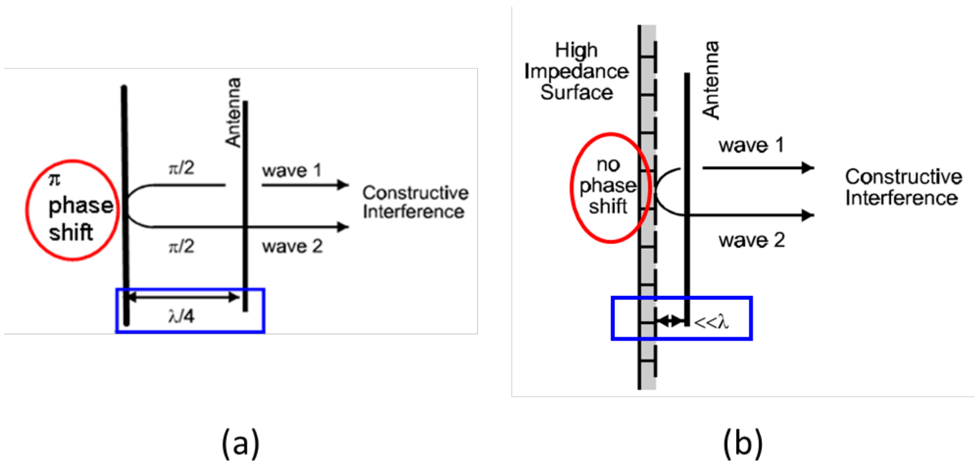

Figure 2 Illustration of the Problem. a) An Antenna Located at λ /4 over a PEC; b) An Antenna Located in Close Proximity of an AMG

The use of an AMG is attractive since the antenna is thinner. However, the mutual coupling between the dipole and the AMG creates some unexpected effects such as erratic behavior of the radiation pattern [4-5]. In addition to that, similar structures were not yet reported to exhibit very wide band behavior (larger than 80%). The information reported in the literature, does not include any discussion about what performance is to be expected from these structures. The benefits of using AMGs over the classical λ /4 structures were not yet addressed and they are not evident. The basic comparison between an antenna above an AMG and the same antenna on a PEC without a matching passive network is not a fair comparison. What we are suggesting is to investigate whether or not an antenna on an AMG can perform better than the same antenna on a PEC when it is optimally matched using a passive-non-dissipative matching network.

To answer these questions, we intend to use Fano's theory [6] to first establish a matching bound for the dipole on a PEC (similar to the one shown in **Figure 2**a), and then to find the same bound for a dipole on an AMG (similar to the one shown in **Figure 2**b). Even though the AMG is not optimized, the calculated matching bound will allow estimating the performance capability of the AMG and also presenting a goal for optimization.

3.1 Objective

3.1.1 First Year Objective

There are numerous design concepts have been published for wideband artificial magnetic grounds (AMGs) and antennas on AMGs. However, they all ignore the mutual coupling between the radiator and the AMG. The published reports simply present the optimization results for bandwidth without any comments on the optimal performance. However, without a better understanding of achievable bounds, the optimization itself is not very productive. The objective of this research concerns the broadband matching limitation for an arbitrary radiator over an AMG by application of Fano's theory. The application of Fano's theory will result in a system of equations that will require a numerical solution for which we will use the recently developed, by the Air Force Research Laboratory (AFRL), the numerical solutions code system called NEMO.

3.1.2 Second year Objective

The theoretical evaluation of the maximum achievable bandwidth for a given physical volume is a significant challenge due to the complexity of the natural frequency response of wide-band radiators. The Fano theory is applied to higher order functions that represent wide-band radiators and find the bandwidth-volume limits.

Fano's theory gives general limits on broadband impedance matching that apply to any given load impedance that can be represented by a finite number of linear passive elements.

3.2 Technical Summary

3.2.1 First Year Summary

During FY 2012 this subtask has included the formulation of the mathematical procedure and its partial implementation in Matlab and HFSS for the maximization of an arbitrary antenna reflection coefficient.

Specifically, the implementation of the mathematical procedure consists of an HFSS simulation of an arbitrary radiator, to generate the reflection coefficient data, which subsequently is used in Matlab to find the zeros and poles of the rational polynomial representation of the reflection coefficient data. This routine is general enough to cope with the reflection coefficient of an arbitrary antenna in general and any radiator on an AMG in particular.

A number of different dipole over AMG configurations were analyzed in HFSS and used to test and validate the robustness of the procedure. An extensive trade-off study between the order of the polynomials used in the function representation, the stability of the solution and the accuracy of the representation was performed. The next step will be to choose the appropriate integral equations, specific to the spectral content of the reflection coefficient (zero types and location) to generate a system of equations which will be subsequently solved to find the maximal realizable bandwidth for a given reflection coefficient goal function.

3.2.2 Second Year Summary

In FY 2013, we devised a numerical procedure to represent a dipole over an Artificial Magnetic Ground by the z-transform of the reflection coefficient function. The procedure was validated using the Finite Elements Method. A desired complex reflection coefficient function was devised and the procedure of the optimization of the Z-transform representation to reach the desired the complex reflection coefficient is in progress. This process allows the calculations of the achievable bounds for wide band circuits and antennas.

3.3 Future Work

Finding the theoretical bound on the achievable matching network is a goal within itself. However, the realization of these matching networks is another goal that will be examined in the last year of this project.

4 Subtask 3: Topics in Transformation Optics and Metamaterials

Metamaterials and transformation optics are two research topics that are of significant importance in electromagnetics. Transformation optics allows us to find the required constitutive parameters associated with spatial coordinate transformation. Metamaterials, which can be described as synthesized materials with constitutive parameters that can be defined macroscopically to a certain practical extent, have given rise to a branch of electromagnetics in its own rights and have provided a conceptual means for realizing the complex media resulted from TO.

For metamaterials, the incorporation of novel materials improves the current trade space for optical devices. One of such novel materials is graphene. Graphene is a one-atom-thick two-dimensional material. In the past, researches have focused on the microscopic/quantum-mechanical aspects of the material, including band structures, transport properties, and conductivity derivation. We propose to study the electromagnetic behaviors of graphene-based structures using Maxwell's equations. In particular, the study of guided waves in graphene-based structures will allow better understanding of how to incorporate them in electromagnetic devices. This will also be an effort to look into the novel electromagnetic theory of a new class of truly two dimensional metamaterials.

4.1 Objective

4.1.1 First Year Objectives

For metamaterials, the incorporation of novel materials improves the current trade space for optical devices. One of such novel materials is graphene. Graphene is a one-atom-thick two-dimensional material. In the past, researches have focused on the microscopic/quantum mechanical aspects of the material, including band structures, transport properties, and conductivity derivation. We propose to study the electro-magnetic behaviors of graphene-based structures using Maxwell's equations. In particular, the study of guided waves in graphene-based structures will allow better understanding of how to incorporate them in electromagnetic devices. This will also be an effort to look into the novel electromagnetic theory of a new class of truly two dimensional metamaterials.

For TO, we propose to analyze the properties of novel antenna with high gain and virtual aperture with TO based metamaterial substrate/superstrate as well as novel ground plane structures. Since the transformed media are inhomogeneous and anisotropic in general, efficient analytical study is needed for canonical cases such as planar, cylindrical and spherical configuration.

4.1.2 Second Year Objectives

The incorporation of electromagnetic materials improves the current trade space for electromagnetic devices. One such material is a metasurface that can be considered as two-dimensional structures which can have tailored response to electromagnetic waves. This is different from electronic band-gag (EBG) based structures as the performance for metasurfaces

is not subjected to the alignment and number of cells used. This will also be an effort to look into the novel electromagnetic theory of a new class of truly two dimensional metamaterials.

For transformation optics, we propose to analyze the properties of novel antenna with high gain and virtual aperture with TO based metamaterial substrate/superstrate as well as novel ground plane structures. Since the transformed media are inhomogeneous and anisotropic in general, efficient analytical study is needed for canonical cases such as planar, cylindrical and spherical configuration.

4.2 Technical Summary

4.2.1 First Year Summary

4.2.1.1 Novel materials

During FY 2012, for this subtask, the guidance conditions for graphene parallel-plate waveguides are examined. Asymptotic expressions are given for all transverse electric (TE) and transverse magnetic (TM) modes with different regions of validity for different frequencies. The behavior of propagation constants at optical frequencies is shown to be different from in the microwave regime due to a difference in conductivities. We show that asymptotic expressions for guided waves in a graphene parallel-plate waveguide using the Lambert W function give good approximations for finding the wavenumber along the propagation direction at optical frequencies for all TM/TE modes. The results from this paper can aid the design of graphene-based devices by providing simple formulas for the propagation constants.

4.2.1.2 Transformation Electromagnetics for Antenna Applications

In FY 2012, we pro-posed a spherical core-shell structure which is able to achieve arbitrarily large directivity. The structure is obtained from coordinates transformation. A large virtual aperture can be projected to free space with a small physical dimension, this subsequently leads to a large directivity. We investigated the problem by finding the trans-formed constitutive tensors and solving the equivalent problem in the core-shell con-figuration. Using the Ricatti-Bessel functions, we can represent the field components with Debye potentials and subsequently solve for the fields in all regions. We applied the formulation to several cases of dipole arrays within the shell, corresponding to both free-space and half-space problems in the virtual space. Both the near field and farfield phenomena were investigated. The relationship between the beamwidths and transmission coefficients for different loss values has been studied and estimation for the cutoffs of the transmission coefficients is provided. Overall, the loss is linked directly to the farfield resolution in terms of the available angular harmonics. It is found that the deterioration of beamwidth changes rapidly with the increase of loss tangent in the shell medium. Even though one can theoretically construct an antenna aperture with arbitrarily high directivity in a small package, based on the specific transformation used here, there is a practical limit as to how strongly a large aperture can be compressed into a small one. It can be reasoned that if a moderate loss tangent value can be reached, a virtual aperture gain should be achievable.

4.2.2 Second Year Summary

4.2.2.1 Novel Electromagnetic Structures

In FY 2013, we used a combination of physical optics (PO) and analytic method to demonstrate focusing with metamaterial lenses. Such lens previously predominantly featured two dimensional structures or stacks of planar elements, both limited by losses which hinder realized gain near the focal region. In this study, we used a plano-concave lens built from a 3D self-supporting metamaterial structure featuring a negative refractive index between 10 and 12 GHz. Fabricated using macroscopic layered prototyping, the lens curvature, negative index and low loss contribute to a recognizable focus and free space gains above 13 dB. With the improved methodology which employs both PO for rapid optimization and numerical method for detail testing, a graded index (GRIN) version is being studied.

4.2.2.2 Transformation Electromagnetics for Antenna Applications

In FY 2013, based on the study of a spherical core-shell structure which is able to achieve arbitrarily large directivity. Overall, the loss is linked directly to the farfield resolution in terms of the available angular harmonics. It is found that the deterioration of beamwidth changes rapidly with the increase of loss tangent in the shell medium. It can be reasoned that if a moderate loss tangent value can be reached, a virtual aperture gain should be achievable.

Current efforts underway include the application of metasurfaces results as well as previous results from virtual aperture and conformal antenna to real antenna scenario. The unique combination of metasurfaces, transformation electromagnetic based structures, and conformal elements to address specifically the issue of angular scan range limitation and beamwidth performance of conformal endfire array on a finite sized structure, with the goal of trying to understand the theoretical aspects as well as the practical implementation of such technologies.

5 Subtask 4: An Electric and Magnetic Dipole Antenna for Zero Backscatter and Low Radiation Quality Factor

The original goal of the effort was to establish performance limits for antennas mounted on structures (e.g. UAS, Micro-UAS, etc.) with sub-wavelength dimensions. However, as discussed in 5.2.1, this goal was revised because other researchers achieved a significant portion of the proposed research. The new goal of this effort is to use analytical and numerical methods to examine the possibility of using a Huygens source (crossed electric and magnetic dipole) to achieve a low Q and/or a low backscatter antenna.

It is well known that the absolute lowest radiation Q can only be achieved by equal excitation of lowest TE and TM spherical modes. There are several papers pertaining to minimum Q electric or magnetic dipole antennas but there is little research regarding the combination of electric and magnetic dipoles for minimum Q. Therefore, one of the goals of this subtask is to address the realizability of such an antenna.

An electric/magnetic dipole antenna is also one of several approaches for realizing a zero or low backscatter antenna. Such an antenna would be very useful as a near field measurement probe because its low backscatter will prevent the probe from perturbing the current on the device under test and, therefore, producing measurement errors.

5.1 Objectives

5.1.1 First Year Objective

The goal of this effort is to establish performance limits for antennas mounted on structures (e.g. UAS, Micro-UAS, etc.) with sub-wavelength dimensions. The theory of characteristic modes will be used to explore how an antenna's radiation quality factor (Q), directivity (D) and impedance bandwidth (B) is limited by the structure on which it resides. We intend develop a method for computing the Q based on the characteristic modes of the antenna/structure which will facilitate the examination of performance limits.

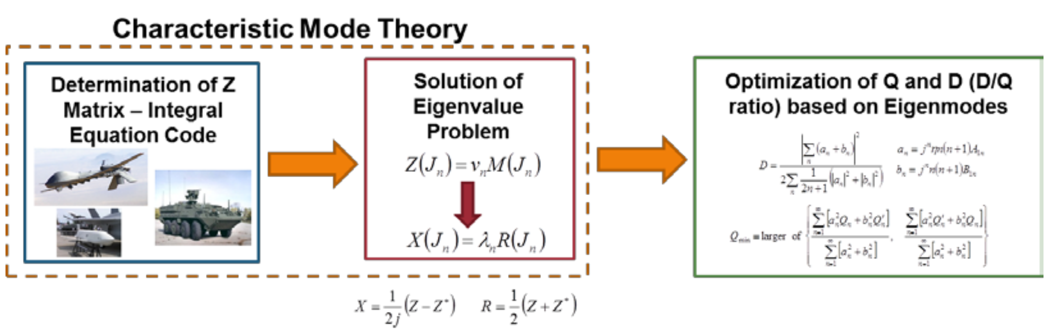

Figure 3 Overview of using Characteristic Mode Theory to Determine Performance Limits for Installed Antennas

5.1.2 Second year Objective

The objective is to use analytical and numerical methods to examine the possibility of using a Huygens source to realize an antenna the can approach the Wheeler-Chu Q Limit and to realize a low or zero backscatter antenna. For this year, the main emphasis was on achieving a low backscatter antenna which can be used as a near field probe that doesn't perturb the currents on the device under test. Both objectives essentially require volumetric antenna designs which are not suitable for most Air Force applications because they are inherently not low profile or conformal. An exception to this is measurement applications where antenna profile or conformality is not a concern.

5.2 Technical Summary

5.2.1 First Year Summary

The main goal of this subtask was to develop expressions for the quality factor and directivity in terms of characteristic modes (CM) and their excitation amplitude and phase. As a first step, a detailed literature search was conducted. It was determined that several antenna pattern synthesis papers based on CMs have existing expressions for D that are adequate and no further development is needed. For the Q, several papers appeared to be computing a quality factor based on characteristic modes. However, it was determined that the quality factor wasn't really a radiation or antenna quality factor.

Over the course of the task, I discovered that a Ph.D. student, Jeffery Chalas, at the Ohio State University had already derived an expression for the radiation quality factor based on CMs. Chalas and his co-authors, K. Sertel and J. Volakis, have submitted a paper titled "Computation of the Q Limits for Arbitrary-Shaped Antennas using Characteristic Modes" to the IEEE Transactions on Antennas and Propagation (no in-formation regarding possible publication date). Early this spring we invited Chalas to WPAFB for a seminar on his CM work. Based on his seminar, he has done extensive work in this area and is currently investigating the concept of using CM in a fast solver algorithm.

As an alternative to the UAS problem, I've been investigating the concept of applying CM analysis to an antenna scattering problem for realizing an antenna with low back scatter. In this context, CM analysis appears to be useful in approaches based on reactive loading for single and multi-mode antenna. However, this approach for achieving low back scatter is inherently narrowband and, therefore, is not as attractive as other approaches. A more promising approach for achieving low back scatter is a Huygens source. Most realizations of Huygens sources have a coupling issue between the antenna elements exciting the electric and magnetic dipole moments. CM analysis was used to examine the coupling issue and it was determined that the dominant coupling mechanism tends to be caused by how the electric and magnetic dipoles are excited and not by the electric or magnetic dipole modes themselves. In the second year, I will examine further implementation issues and investigate the possibility of utilizing a Huygens source as a low Q antenna.

5.2.2 Second Year Summary

There are two fundamental methods for reducing antenna scattering. Firstly, antenna scattering can be reduced by reducing the total scattered power which reduces scattering over all visible space. The second approach is to only reduce scattering over a limited angular region. For antenna scattering, the first approach has a significant shortcoming in that a reduction in the total scattered power (or bistatic cross-section) is always accompanied by a reduction in the absorbed power (absorption cross-section) [7-9]. Therefore, a low scattering antenna based on the first approach is limited to applications where there is little noise or the noise is controllable (i.e. a controlled environment often found in most measurement systems). The second approach can reduce scattering over a limited solid angle, typically in the back half-space, without a reduction in the absorbed power. The main disadvantage of this approach is that the forward scattered field is significantly increased but this is not major issue for most applications.

For the majority of applications, the second approach is superior and it was the focus of my effort in the second year. The second approach is based on the concept of utilizing multiple antenna modes to reduce the back scattered field from the antenna by controlling the amplitude and phase of each mode. A classic example of a multi-mode antenna is the Huygens source which is a crossed electric and magnetic dipole. In the second year, an analytical examination of the radiation and scattering properties of an ideal Huygens source were examined. It was determined that the total scattered power was substantially affected by the excitation magnitude and phase of the electric and magnetic dipoles. However, the back scattered field is not dependent upon excitation phase. It only depends upon the ratio of the excitation amplitudes which is a promising result from a bandwidth perspective because it is easier to hold an amplitude constant over a given bandwidth than it is to maintain both amplitude and phase.

The remainder of the second year was devoted to implementing the Huygens source. An extensive literature review of electric and magnetic dipole sources was conducted and several candidates were found. Many of these dipole sources were evaluated to determine their suitability for use in a Huygens source. The most promising antenna was the folded multi-arm spherical helix (FMSH) [10] because it can support both electric and magnetic dipole modes depending upon how it is excited (see Figure 4). Initial results indicated that it is capable of achieving low or zero backscatter but it is not clear if this can be maintained over a broad bandwidth. The main impediments for broad band operation are coupling between the feeds of the electric and magnetic dipoles and being able to excite the magnetic dipole mode over a broad bandwidth without exciting higher order modes.

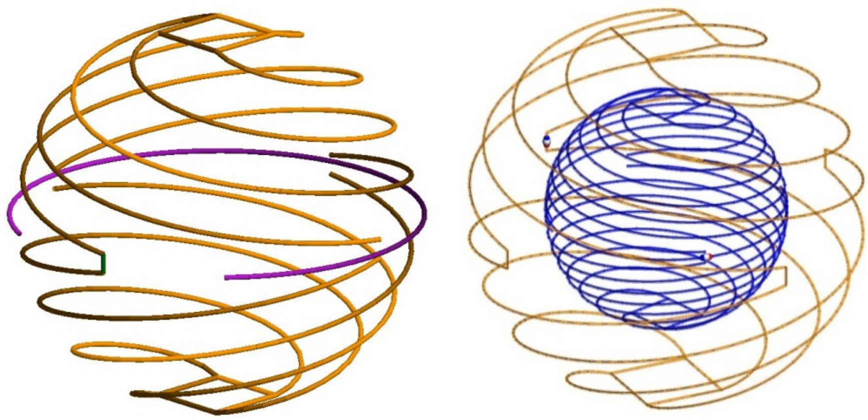

Figure 4 Examples of Multi-arm Spherical Helices that Excite an Electric and Magnetic Dipole Mode

5.3 Future Work

In the last year of this project I will complete the effort to realize a zero or low back scatter antenna. The main issue that needs to be addressed is the bandwidth. The goal is to improve antenna bandwidth by addressing issues with coupling between the feeds of the electric and magnetic dipoles and pure excitation of the magnetic dipole mode over a broad bandwidth (eliminated higher order modes is possible). The second objective is to investigate the potential of this design to approach the Wheeler-Chu Q limit for a dual mode antenna. Since the antenna will store energy inside the spherical volume it occupies, it will not be able to achieve the Wheeler-Chu limit but, instead, it will come within an undetermined multiplicative factor (i.e. 2 times the Wheeler-Chu limit). The goal is therefore to determine this multiplicative factor.

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List of Acronyms, Abbreviations, and Symbols

Acronym	Description
AFRL	Air Force Research Laboratory
AMG	Artificial Magnetic Grounds
CM	Characteristic Modes
CSWAP	Cost, Size, Weight and Power
D	Directivity
dB	Decibels
EBG	Electronic Bandgap
EM	Electromagnetic
FEM	Finite Element Method
FMSH	Folded Multi-arm Spherical Helix
FY	Fiscal Year
GHz	Gigahertz
GRIN	Graded Index
HFSS	High Frequency Structural Simulator
MHz	Megahertz
NEMO	Numerical Electromagnetic Optimizer
Ω	Ohms
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
PO	Physical Optics
Q	Quality Factor
STO	Source Transformation Optics
TE	Transverse Electric
TM	Transverse Magnetic
TO	Transformation Optics
UAS	Unmanned Aircraft System
λ	Wavelength